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Adaptation to climate change in perennial cropping systems: Options, barriers and policy implications

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ABSTRACT

Plantation crops are likely to be highly vulnerable to climate change because of their long economic life span, their typically non-irrigated cropping pattern and the inability to easily switch crops due to high upfront capital costs. Hence the sector requires appropriately designed adaptation options to cope with on-going climate change. Studies on climate adaptation in perennial cropping systems are rare relative to those on annual crops. Based on a cross-sectional survey of 50 tea estate managers representing all tea growing areas in Sri Lanka, this study analyses factors affecting choice of preferred adaptation options, barriers to adaptation and associated policy implications for tea production as an example of a perennial tree crop system. Current adaptation options identified are crop diversification, soil conservation, and shade tree establishment and management. All of these options are adopted in some situations and locations. All estate managers interviewed believe that climate change is happening and almost all are experiencing the negative impacts of climate change on tea production. Results from a multinomial logit analysis show that information on climate change, company size, tea growing elevation, and increases in temperature and rainfall are key factors influencing the preferred choice of adaptation option. Furthermore, results reveal that barriers such as a lack capital, inadequate access to near-term and medium-term climate knowledge, and poor governmental and institutional support may prevent estate managers from experimenting with new adaptation options. Policies should, therefore, be aimed at promoting new adaptation options through information exchange between a wide range of stakeholders, and integrating climate change adaptation with Sri Lanka's sustainable developmental goals. Governmental and institutional support and involvement would be instrumental in facilitating adoption of adaptation options such as joint-production of tea with valuable timber crops.

1. Introduction

Adaptation can be considered to be the search for 'a better fit' to changed conditions (Arthur and Van Kooten, 1992; Smit et al., 2000), and can be either incremental ('tinkering around the edges' of current practices), or transformative (deeper, more structural changes) (Moser and Ekstrom, 2010). Effective adaptation to the particular stressors imposed by climate change is likely to require the latter approach (Rickards and Howden, 2012). Transformative change is particularly challenging for the perennial plantation sector. The establishment of plantation crops is a lengthy process requiring considerable capital investment, particularly in comparison to annual crops. This typically constrains options for climate change adaptation such as crop switching (Burton and Lim, 2005; Lobell et al., 2006; Lobell and Field, 2011). In addition, plantation crops such as tea, rubber and coconut are typically rain-fed (non-irrigated). The distinct differences between annual and perennial crop farming, and the important role which perennial cropping plays in developing world agriculture, suggest that it is important to understand the factors which affect farmers' choice of climate adaptation options in both annual and perennial crop farming.

Agrawal and Perrin (2009) argue that adaptation can happen from the top-down through changes in policies and institutions, and from the bottom-up via individual farm-level responses. Thus, agricultural adaptation can result from an intentional proactive or reactive response to any risk or change which modifies the business environment (Bryant et al., 2000). Many studies have analysed factors affecting farmers' choice of climate adaptation options in annual crop and livestock production systems in different parts of the world. Seo and Mendelsohn

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(2008) estimate a multinomial logit model (MNL) of crop choices using data collected from 949 farmers across seven South American countries. They find that variations in temperature and rainfall are key determinants of decisions to switch between crops such as vegetables, fruits and rice. Similarly, Deressa et al. (2009) employ a MNL to identify the determinants of farmers' choice of adaptation options under climate change in Ethiopia, based on a cross-sectional household survey of 1000 farmers. The authors find that education, gender, age, farm income, non-farm income, information on climate change, access to extension services, agro-ecological setting and temperature are significant determinants of adaptation choices. Based on a survey of 546 rice farmers, Alam (2015) explores factors affecting choice of adaptation options for water scarcity in a semi-arid region of Bangladesh. The author finds that more experience, better schooling, better access to electricity and institutional facilities, greater awareness of climate effects and secure tenure rights are key determinants of choice of alternative adaptation strategy. In a livestock farming context, Kabubo-Mariara (2008) investigate factors that affect choice of different livestock species under climate change in Kenya. The study finds that annual temperature, rainfall, age of head of household, household size and average education level of the household are the key drivers of livestock species choice.

To the best of our knowledge, no studies have yet empirically investigated the drivers of adaptation choice in perennial agriculture. Tea is an example of a perennial crop with an economic life span of about 30–50 years, and is a crop which provides a major source of revenue and employment in a number of developing countries (Alkan et al., 2009; Brouder et al., 2014). A number of studies have discussed the impact of climate change on tea production (Costa, 2010; Gunathilaka et al., 2017; Wijeratne, 1996), and whilst these studies mention potential adaptation options, they provide very little empirical analysis of the drivers of adaptation choice. To fill this knowledge gap, the present study analyses Sri Lankan tea estate managers' perceptions of climate change impacts, factors which affect their choice of current and potential future adaptation options, and barriers to the uptake of these options. The Intergovernmental Panel on Climate Change (IPCC) predicts increases in precipitation, temperature and extreme weather events for South Asia by 2060 (IPCC, 2013). The productivity of agricultural crops is predicted to decline, leading to increases in the vulnerability of rural communities who are dependent on agriculture for their livelihood. To the best of our knowledge, this is the first study to analyse factors affecting estate managers' choice of climate adaptation options for plantation crops in a developing country context.

Tea is the foremost agricultural crop in Sri Lanka. The tea industry generates about 15% of national foreign exchange earnings and provides employment for about 7% of the total workforce. Over 600,000 employees and their dependents rely on the tea sector for their livelihood (Ministry of Plantation Industries, 2013). The plantation crop sector in Sri Lanka has, however, been adversely affected by changes in climate over recent decades (Central Bank of Sri Lanka, 2014; Gunathilaka et al., 2017; Wijeratne and Chandrapala, 2014). Both the larger plantation estate sector and the smallholding sector face challenges from climate change, raising questions about their long-term viability. The quantity and quality of tea are greatly influenced by climatic parameters, particularly rainfall and temperature (Boehm et al., 2016; Wijeratne et al., 2007). Therefore, in Sri Lanka there is particular concern over the tea sector's vulnerability to climate change (Costa, 2010; Wijeratne, 1996).

Comprehensive knowledge of available adaptation options is of utmost importance if estate managers are to counteract production losses from climate change and maintain the competitiveness of Sri Lankan tea brands in the international market. This is also vital for efficient and effective channeling of available resources to address the consequences of climate change. Employing data derived from face-to-face interviews with 50 tea estate managers in Sri Lanka, this study focuses on the following research questions: (i) What are estate managers' perceptions of climate change? (ii) Which adaptation options are estate managers currently adopting? (iii) Which factors influence the choice of preferred adaptation options? And (iv) What are the policy implications of preferred adaptation options for long-term sustainability?

The paper is structured as follows: Section 2 describes the study area, data and survey sample characteristics. Section 3 reports managers' observations of the impacts of climate change on tea plantations. Section 4 describes a multinomial logit model of climate adaptation choice and presents multinomial logit results. Section 5 discusses constraints on the choice of adaptation options, and Section 6 concludes with policy implications.

2. Study area and data collection

2.1. Sri Lanka's tea sector: context and challenges

Historically, Sri Lanka's tea plantations were owned and developed by the British, and managed by British private companies (Loh et al., 2003). Between 1972 and 1975, however, all foreign and locally-owned estates larger than 20 ha were acquired by the government and vested under the Janatha Estate Development Board (JEDB) and the Sri Lanka State Plantations Corporation (SLSPC). JEDB and SLSPC managed 509 tea, rubber and coconut estates under the purview of the Ministry of Plantation Industries. Nationalised management through JEDB and SLSPC was not successful, and as a consequence between 1992 and 1993 the 509 estates were clustered into 23 Regional Plantation Companies (RPCs) with ownership of these companies retained by the government. Initially, management of RPCs was based on 99 year leases, with 5 year management agreements with private agents. This short term management agreement proved insufficient to motivate adequate investment, and financial performance continued to be poor. In 1995 Government divested ownership of all RPCs to the private sector, while retaining ownership of the land on a shortened lease agreement of 50 years (Kularatne and Takeya, 2003).

Currently, there are 306 tea estates scattered across three major growing regions of the country, owned and operated by 21 different RPCs.[1] Individual tea estates are managed centrally by a plantation company and usually possess their own processing facilities. This level of vertical integration constrains opportunities for crop switching as a climate adaptation strategy.

Further constraints on adaptation arise from the structure of the estate labour market. The estate sector operates with a large residential workforce who typically comprise Tamils originally brought from South India to Sri Lanka during British colonisation (Duncan, 2002). Labour operates under a centralized wage system, whereby plantation companies are required to increase the wages of plantation workers every three years (Sinnathamby, 1993). The number of workers and workdays in the estates are fixed for registered workers regardless of production, and worker productivity has not kept pace with wage increases; compared to other tea producing countries, Sri Lanka's plantation workers harvest approximately 18 kg/labour day, while workers in Kenya, South India and Assam harvest 48, 38, 26 kg/labour day, respectively. As a consequence, Sri Lankan tea estates tend to deploy labour only for essential management practices, such as tea plucking, and ignore capital-intensive sustainable management operations such as soil conservation and replanting.

Sri Lanka is part of the Indian sub-continent and has a tropical climate. Tea growing areas are located in Sri Lanka's wet zone (annual average rainfall − > 2500 mm) and intermediate zone (average annual rainfall − 1750–2500 mm). Plantation areas receive most rain during two major monsoons: the South-West Monsoon between May and September, and the North-East Monsoon between December and

[1] The remaining two RPCs only manage coconut plantations, not tea.

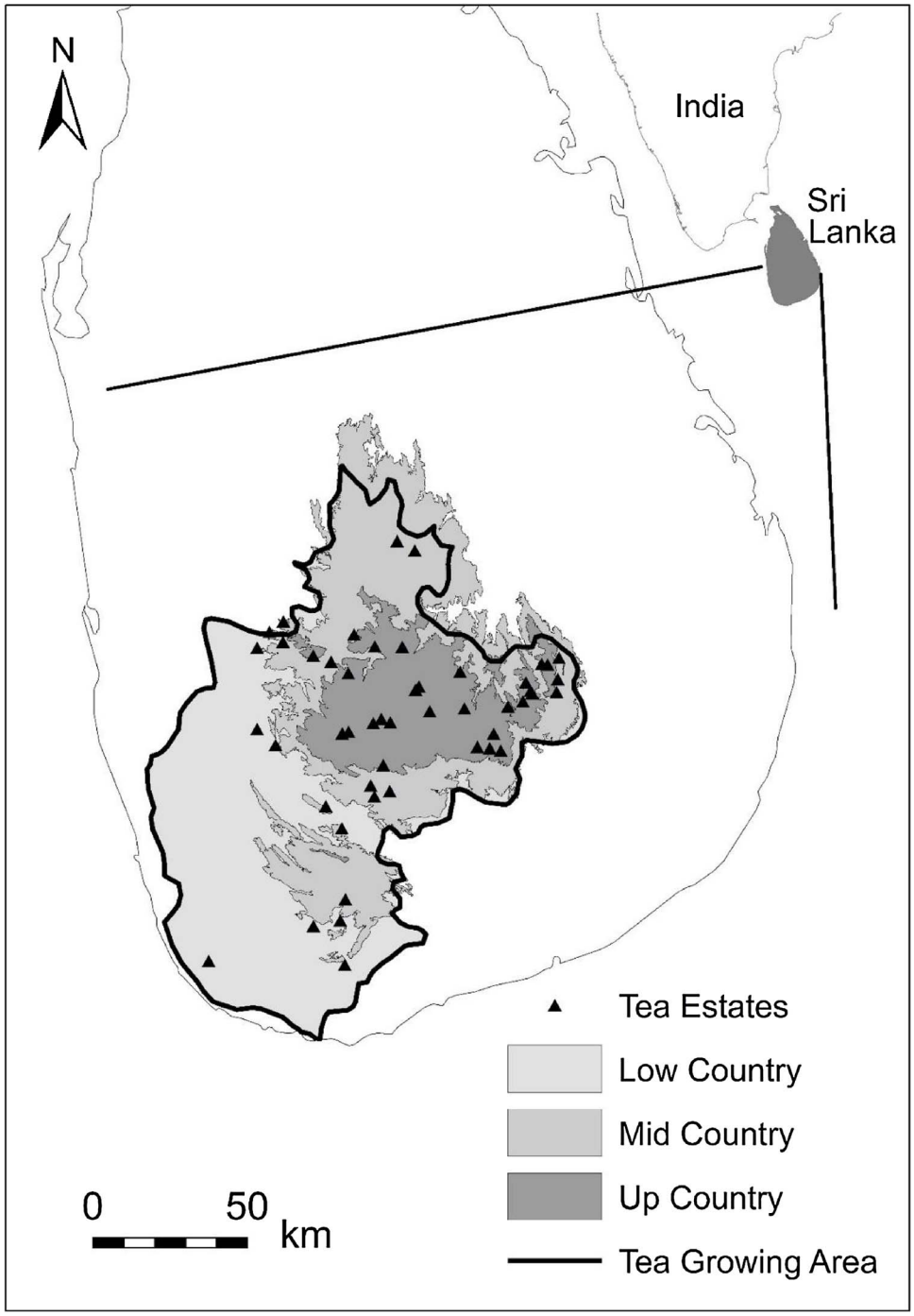

Fig. 1. The estates surveyed at each elevation in tea growing areas of Sri Lanka.

February. Inter-monsoons also bring evening showers; hence peak tea production is normally recorded during these inter-monsoonal periods due to favourable conditions of soil moisture and sunshine. Average temperature varies with elevation, from around 28 °C in the lowlands ('low-country'), to approximately 20 °C at mid elevations ('mid-country' between 300 m and 900 m), and 16 °C at higher elevations ('up-country'). Our study focusses only on the estate sector, rather than small holders, because time series data on climate, labour and production performance are available, and because the unique nature of the estate-resident labour force makes these workers particularly vulnerable to the consequences of a changing climate.

2.2. Survey

To obtain a representative sample of Sri Lanka's 306 tea estates, in-depth semi-structured interviews were conducted on site with managers from 50 estates across Sri Lanka's three tea-growing regions (Fig. 1). Sites for data collection were chosen to cover 20 of 21 agro ecological regions (AER) containing tea estates in Sri Lanka, and to encompass wide variations in rainfall, temperature and elevation. The interviews took place between February and May 2015 and obtained data detailing the age and experience of managers, managers' observations of changes in weather and climate over their years in the industry, managers' perceptions of climate change and climate-related risks to their estates, managers' responses to climate change, constraints to adaptation and potential adaptation options. Interviews typically lasted about 40 min.

All interviews were recorded and then transcribed for subsequent analysis.[2] To obtain another perspective of potential adaptation options and constraints, three chief executive officers who manage eight regional plantation companies were also interviewed.

3. Results

3.1. Sample characteristics

All estate managers interviewed were male. This is to be expected because plantation management in Sri Lanka is heavily male dominated (Sivaram, 2000). Mean managed estate size was 322 ha (s.d. 131 ha), and managers were interviewed in all tea growing regions of Sri Lanka. Almost all of the 50 tea estate managers interviewed had more than 10 years of experience, and 26 managers had more than 20 years of experience in plantation management. Most managers were over 30 years of age and 92% had secondary-level education. Demographic characteristics of survey respondents are shown in Table 1.

Table 1
Characteristics of sample respondents.

Individual characteristics	%
Age group	
20–29	4
30–39	28
40–49	38
50–59	24
60+	6
Managerial experience	
1–9 years	2
10–19 years	46
20–29 years	38
30–39 years	6
40–49 years	8
Education level	
Secondary	92
Degree/Diploma	8
Heard of the term climate change before?	100
Do you have sufficient information about climate change?	18
Access to longer-term climate projections?	26
Views about climate change	
I think that climate change is ongoing	100
I believe that human activities are mostly contributing to climate change	92
We are more affected by regional changes in climate than by global changes	66
Preferred climate adaptation option	
Crop diversification	38
Soil conservation	32
Shade management	30

3.2. Respondents' observations of changes in climate

From data obtained during the in-depth interviews, estate managers have observed changes in the patterns of temperature, rainfall and extreme climate events (i.e. drought and high intensity rainfall). Tea growers are concerned by changes in weather patterns because the volume and quality of tea depends strongly on these patterns, and they also influence many operational management decisions (Boehm et al., 2016).

As indicated in Table 1, all survey respondents had heard of the term 'climate change' or 'global warming' and 78% of respondents reported personal experience of changes in rainfall patterns, the timing of monsoons and the frequency of occurrence of extreme weather events compared to about 15 or 20 years ago. All respondents recalled years and periods characterised by drought and heavy intensity rainfall. Lack of information was mentioned as a primary constraint on adaptation action by 82% of respondents, with only approximately a quarter of respondents (26%) having access to longer term climate projections. The interviews were conducted at the estate offices and all of the offices had charts of decennial monthly rainfall and number of wet days displayed prominently.

All respondents believed that climate change is occurring, while 92% believed that human activities are responsible. Of the 50 respondents, 33 believed that the consequences they have observed arise due to regional change in climate, whereas 17 believed that observed consequences are the result of global changes in climate. Nearly all respondents (98%) said that they were experiencing the impacts of climate change on tea production. The changes in weather patterns in Fig. 2 were considered to be a consequence of climate change. All respondents said that they were undertaking adaptation options in an attempt to reduce financial losses due to climate change; however, managers' preferred adaptation options differed.

3.3. Respondents' observations on climate impacts

Respondents were asked to identify which particular climate change impacts they had observed on tea production during their time in estate management. When asked how sensitive tea production was to climate change on a 5-point Likert scale, 96% of managers said production was 'very sensitive' to climate change and the remaining 4% said that it was 'sensitive' to climate change.

Ninety eight percent of respondents stated that observed climate changes had negative consequences for tea production. Poor recovery of tea bushes leading to no or reduced crop, and wider distribution of pest, diseases and weeds were two commonly-cited adverse impacts:

> "*In low country estates, we have never experienced blister blight. I took over this estate in 2008 and until 2012 we never had blister blight, however, this year and last year we had lot of blister, compared to last year, this year it is severe, we lost so much of crop due to blister because we were not ready with chemical spraying because we did not have this much severe blister blight earlier, so, I must say that the distribution of pest and diseases have changed due to climate change*". [Manager #31, Low-country]

Some managers reported occasions when estates were unable to provide assured work for their casual labour force during drought. This reduces income security amongst poor rural workers:

> *"last year this time we could not offer work continuously, we had to cut down two or three work days per week"*. [Manager #9, Up-country]

Approximately two thirds of respondents said that soil erosion has accelerated due to prolonged drought followed by high intensity rainfall:

> *"even after a hell of a rain, our soil is dry, water does not retain in soil because top soil is washed off" ……."earlier we normally could start fertilizing after about two or three days of rain but now we are unable to do fertilizing after a rain because soil is dry"*. [Manager #38, Low-country]

Ninety percent of respondents said that they were experiencing poor attendance of field workers during excessive rain periods, and that they have to reduce working hours during thunderstorms because of the risk of lightning strikes. Managers also mentioned that production declines during excessive rains as a result of extended periods of cloud cover.

Many managers (76%) believed that the quality of processed tea declined due to extreme weather events:

> "*we are unable to make good tea during excessive rainy periods because of high water content in leaves, however we can make fine teas in dry weather and fetch good price, but, prolonged drought hampers production and even premium price cannot counteract losses due to drop in*

[2] Ethics approval for the study was granted by [details removed for blind review]. All participants in this research provided their informed consent.

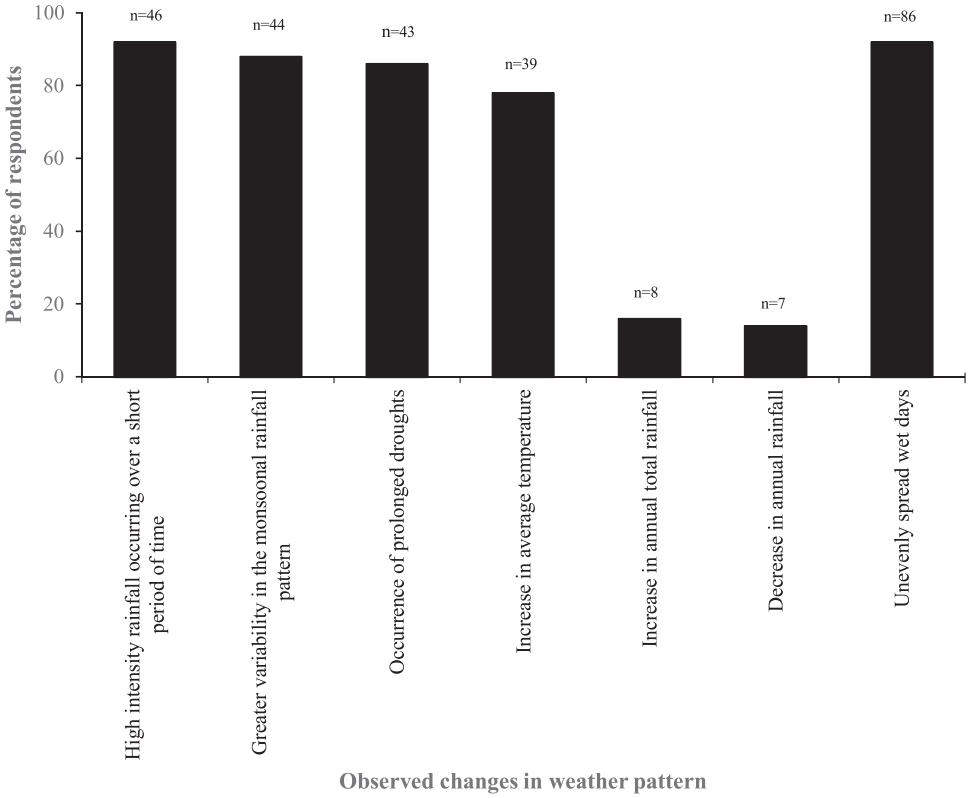

Fig. 2. Managers' observed changes in weather. The data labels show number of respondents.

production during droughts". [Manager #30, Up-country]

Managers were asked about the effects of climate change on the 'quality season', that time of year when a particular region is able to produce its highest quality tea. Excessive rain during quality seasons was identified as a negative consequence of climate change. Specifically, managers in the Up-country (Uva and Nuwara Eliya areas) responded that in recent years they did not have a proper quality season due to heavy rains or prolonged drought:

"It's sad, quality season has also been affected since recent years, we expect few showers only and blowing during July to September, last year it was a prolonged drought". [Manager #21, Up-country]

Eighty eight percent of respondents mentioned that extreme weather events increased production costs, as clearly indicated by the following statement:

"*During drought, we come across more off grades of processed tea, we don't get much crop, during heavy rains we can't expect much quality, so our cost of production is very high during those extreme weather events*" [Manager #41, Up-country]

In summary, the survey reveals that Sri Lankan tea plantations are experiencing negative consequences from climate change, in particular, increased costs of production, low production volumes and poor quality of tea, together with negative social consequences from reduced labour demand.

3.4. Adaptation options

Plantation managers stated that they have been carrying out a number of adaptation options to counteract the impacts of climate change. These options include crop diversification, soil conservation and shade tree management (Table 1).

"I think crop diversification is a good strategy for adaptation. We have identified some blocks to plant Eucalyptus. We are doing fuel-wood in a large scale. We have only selected marginal tea lands for diversifying with coffee." [Manager #20, Mid-country]

"We practise soil conservation measures: Sloping Agricultural Land Technology system, terraces and draining wherever possible and plant grasses in bare lands." [Manager #26, Up-country]

"Specially, in low country we should plant low shade and high shade. I believe it as a mandatory requirement. Because force of the rain is high and if it directly comes into the soil it will badly affect for tea." [Manager #18, Low-country]

The three adaptation options were identified as their preferred option by roughly equal proportions of managers. For example, 38% of managers indicated crop diversification as their preferred adaptation option. Rubber, cinnamon, pepper, mandarin, cloves, cardamom and eucalypt species for fuel wood are commonly chosen. Soil conservation practices are the preferred option for 32% of the managers. Plantation managers assist soil conservation by adopting cultivation practices such as drainage (constructing and maintaining leader and lateral drains), mulching, cover cropping, planting rehabilitation grasses and incorporation of green manures. These soil conservation methods help to conserve soil moisture and reduce soil temperature. Shade management is the preferred adaptation option of 30% of the managers. Tea requires a certain level of shade for optimum growth and productivity. Shade trees are thus an important means of controlling temperature and protecting tea bushes from high intensity rainfall.

4. Identifying determinants of adaptation choice

Across the Sri Lankan survey sample, tea estates have chosen soil conservation, shade tree management and crop diversification as adaptation options. Our MNL analysis seeks to identify factors which influence estate managers' choice of preferred adaptation option. In this section, following standard practise in the literature, an MNL is used to identify factors which influence estate managers' choice of preferred adaptation option on their tea plantations in Sri Lanka.

In the MNL model, the dependent variable (i.e. preferred adaptation option) is a random categorical variable y with 1, 2, …, J discrete values. Let $\mathbf{z}$ denote a vector of explanatory variables that differ across the individuals making the choices. Here $\mathbf{z}$ consists of different characteristics of the manager, estate and its environment. Assuming that the response categories are mutually exclusive and exhaustive, we have response probabilities $P(y = j \mid \mathbf{z})$, $j = 1, 2, \ldots, J$, which add up to one, and we have J-1 parameters. The MNL specifies for choice $j = 1, 2, \ldots, J$:

$$P(y = j \mid \mathbf{z}) = \frac{\exp(z\beta_j)}{1 + \sum_{h=1}^{J} \exp(z\beta_h)} \quad (1)$$

Adaptation responses are as described in Section 3.

Marginal effects of the explanatory variables are obtained by differentiating Eqn 1 with respect to the individual-specific explanatory variables. Choice probabilities are expressed relative to the probability of a base adaptation category − in this case, crop diversification. The derivatives of the choice probabilities provide a measure of the expected change in the probability of choosing a particular adaptation option following a unit change in an explanatory variable. For example, the marginal effect of explanatory variable x on the probability of choosing adaptation option k can be expressed as follows.

$$\frac{\partial P_j}{\partial x_k} = P_j\left(\beta_{jk} - \sum_{J}^{j-1} P_j\beta_{jk}\right) \quad (2)$$

4.1. Specification of model variables

Potential explanatory variables were selected based on the literature, data availability and information obtained through the interviews. Key factors that could drive the choice of adaptation options can be broadly categorized as: climatic variables appropriate to the location of the estate (average annual temperature, average annual rainfall); elevation of the estate (up-, mid- and low-country); size of the parent company which owns the estate; and access to information on climate change. Explanatory variables used in the empirical estimation are described in Table 2. Estate managers expressed that they had observed changes in temperature, rainfall and occurrence of extreme climate events. Regression analysis therefore explored whether recorded changes in average temperature and total rainfall between 1990 and 1995 and 2009–2014 influenced the probability of estate managers preferring a particular adaptation option. Estate managers also expressed concern regarding access to longer term climate change projections; access to climate change information was therefore also included.

4.2. Drivers of preferred climate adaptation options

Various combinations of potential explanatory variables were tested and a final model was selected based on model fit, change in likelihood ratio and statistical significances. The selected model was tested for multicollinearity using variance inflation factors (VIF). VIFs for all explanatory variables (1.11–1.49) are well below the standard threshold of concern (10) (Wooldridge, 2013), confirming that the parameter estimates are unbiased.

Table 3
Parameter estimates of the multinomial logit model of managers' preferred choice of climate adaptation option.

Explanatory variables	Soil conservation		Shade	
	Coefficients	*P* level	Coefficients	*P* level
Information on climate change	2.751**	0.022	2.469*	0.074
Large company	−2.527**	0.031	−2.961**	0.016
Tea growing elevation −				
Mid	−0.833	0.507	1.358	0.276
Low	−1.762	0.150	−0.563	0.667
Increase in temperature	3.091***	0.009	2.857**	0.014
Increase in rainfall	0.0002	0.773	0.0009	0.164
Constant	0.291	0.734	−0.679	0.517
Diagnostics				
Base category for climate adaptation	Crop diversification			
Number of observations	50			
LR chi-square	34.19			
Log likelihood	−37.58			
Pseudo R^2	0.31			

***, **, * Significant at 1%, 5% and 10% probability level, respectively.

The model was also tested for the validity of the independence of irrelevant alternatives (IIA) assumption by employing the seemingly unrelated postestimation procedure (SUEST), which is the recommended test of IIA for small samples (Weesie, 2000). The p value of the SUEST test ranges from 0.82 to 0.91, depending on which adaptation option is excluded. The SUEST test thus fails to reject the null hypothesis of IIA, indicating that the MNL model is appropriate for modelling tea estate managers' choice of preferred climate adaptation option. The chi-squared statistic (χ^2) of the resulting model is highly significant ($p > 0.0006$), suggesting strong explanatory power. Model results are shown in Tables 3 and 4. In MNL models the most important results are the marginal effects (Table 4) rather than the parameter estimates of the explanatory variables (Table 3).

4.2.1. Information on climate change

Marginal effects reported in Table 4 indicate that information on climate change has a significant and negative impact on the likelihood of preferring crop diversification as the adaptation option. Specifically, estate managers who indicate that they have received information on climate change, have a 46.5% lower probability of choosing crop diversification as their preferred adaptation option.

4.2.2. Large company

Estate managers employed by large companies are 59% more likely to prefer crop diversification, than estate managers employed by smaller companies. Whereas, estate managers employed by large companies were 32.8% and 26.2% less likely to prefer shade

Table 2
Independent variables in multinomial logit analysis.

Variable	Mean	S.D.	Description
Information on climate change	0.280	0.454	Dummy, 1 = yes, 0 = otherwise
Large company	0.360	0.485	Dummy, 1 = large, 0 = otherwise A large company is defined as a company which earns > 3 billion LKR* revenue and > −3% for five-year average net profit margin
Elevation	1.740	0.777	Categorical, 1 = up, 2 = mid, 3 = low
Increase in annual average temperature (°C)	0.114	0.604	Continuous, expressing the change in average temperature between the years 1990–1995 and 2009–2014
Increase in annual total rainfall (mm)	198.22	809.37	Continuous, expressing the change in average annual rainfall between the years 1990–1995 and 2009–2014

* LKR = 'Sri Lankan Rupees' and 153 LKR = 1 USD $ [@ 2017 September exchange rates].

Table 4
Marginal effects from the multinomial logit climate adaptation model.

Explanatory variables	Crop diversification		Soil conservation		Shade	
	Marginal effects	*P* level	Marginal effects	*P* level	Marginal effects	*P* level
Information on climate change	−0.465***	0.002	0.300	0.178	0.166	0.486
Large company	0.590***	0.001	−0.262*	0.083	−0.328**	0.019
Tea growing elevation −						
Mid	−0.053	0.799	−0.334*	0.082	0.388*	0.062
Low	0.312	0.213	−0.339*	0.073	0.027	0.876
Increase in average annual temperature†	−0.231**	0.022	0.143***	0.000	0.088***	0.000
Increase in average annual rainfall†	−0.064***	0.000	−0.050***	0.001	0.114***	0.000

***, **, *Significant at 1%, 5% and 10% probability level, respectively.
†Indicates one standard deviation discrete increase from the mean.

management and soil conservation, respectively, as adaptation options.

4.2.3. Tea growing elevation

Broadly, tea estates in different tea growing elevations employ different adaptation methods as appropriate for the temperature and rainfall at their elevation. For example, managers of tea estates in mid- and low-country were 33.4% and 33.9% less likely to prefer soil conservation as an adaptation approach, compared to managers of up-country estates (the reference elevation category). Further, managers of mid-country tea estates are 38.8% more likely to prefer shade as an adaptation option compared to managers of up-country estates.

4.2.4. Increase in average temperature

Managers of estates which have experienced larger increases in average temperature between 1990 and 1995 and 2009–2014, are considerably less likely to prefer crop diversification as an adaptation option. For a one standard deviation increase in annual temperature, the probability of an estate manager preferring crop diversification decreases by 23.1%, holding other independent variables constant at their means. Whereas, the probability of a manager preferring soil conservation and shade management as adaptation options increases by 14.3% and 8.8% respectively.

4.2.5. Increase in annual average rainfall

In contrast to the impact of rising temperatures, managers of estates which have experienced larger increases in average annual rainfall were more likely to choose shade management as their preferred adaptation option. A one standard deviation increase in rainfall increases the probability of an estate manager preferring shade management by 11.4%, holding other independent variables constant at their means.

5. Constraints on choice of adaptation option

Using information gathered through the in-depth interviews with the estate managers, we present a qualitative analysis of constraints and challenges which confront estate managers in implementing adaptation options. As might be expected, the most common constraint (expressed by 94% of respondents) was a lack of capital to invest in climate adaptation options (Fig. 3):

> *"companies are struggling to survive, we are not in a position to spend much for adaptation options since our cost of production is really high, we need to economically survive, however we believe that adaptation is necessary for sustainability"*. [Manager #33, Up-country]

This indicates that managers recognise the need for adaptation, and would potentially be willing to take up adaptation options, however as many estates lack sufficient operating surpluses, opportunities for implementing adaptation options are severely constrained. Almost all respondents who stated insufficient capital as the main constraint on adaptation said that they would be willing to accept any assistance offered by the government or any other parties. Of respondents constrained by a lack of investment capital, 86% said that they were unable to fully implement their chosen adaptation option because of a lack of funds. The majority of respondents held the view that if there were established incentive schemes for adaptation, more estates would be willing to implement appropriate adaptation actions.

One potential source of capital to facilitate adaptation could be joint production of tea alongside fast-growing timber trees to access carbon credit payments. Under existing regulations, tea estates are excluded from the carbon trading process, thus locking them out from these potential revenue flows:

> *"Carbon sequestration has been much talked about. But nothing has come out of it. People have come out of proposals 5–6 years back but nothing has come, the matter is there is a procedure to enter into an agreement but that incurs high cost for obtaining it. If we could have a simple mechanism to go for it we are willing to get it…… as I am aware, cultivated crops are not included under the carbon trading process. However, if there is government and related institutional support to implement it, plantations are willing to go for it" [Chief Executive Officer − major tea plantation company, operating estates across all elevations]*

A lack of information was mentioned as a primary constraint on adaptation action by 82% of respondents, this suggests that current information and awareness programmes regarding climate change and its impacts on tea production may be inadequate. Approximately three quarters of respondents (74%) said they obtained weather information only via daily forecasts and were not aware of any near-term or medium-term climate predictions. Other than information obtained through daily weather forecasts, internet and television, there appears to be no adequate source of information or extension services regarding climate change impacts on the tea sector. Approximately three quarters of managers (76%) also mentioned that they are not aware of any sources of this information other than from extension services related to tea:

> *"we need more and more awareness and information for adaptation options so we could try out and see", "awareness programmes and information on especially climate change is totally lacking"*. [Manager #3, Low-country]

Furthermore, managers said that they were advised by the Tea Research Institute to go for soil conservation and shade management as adaptation options, reserving crop diversification for marginal tea fields identified during the tea pruning cycle. This is consistent with the MNL finding that estate managers who had received information on climate change impacts (predominantly from tea extension services) were almost 50% less likely to prefer crop diversification as an adaptation option.

The third most commonly-stated constraint on climate adaptation was a lack of government and institutional support. For example:

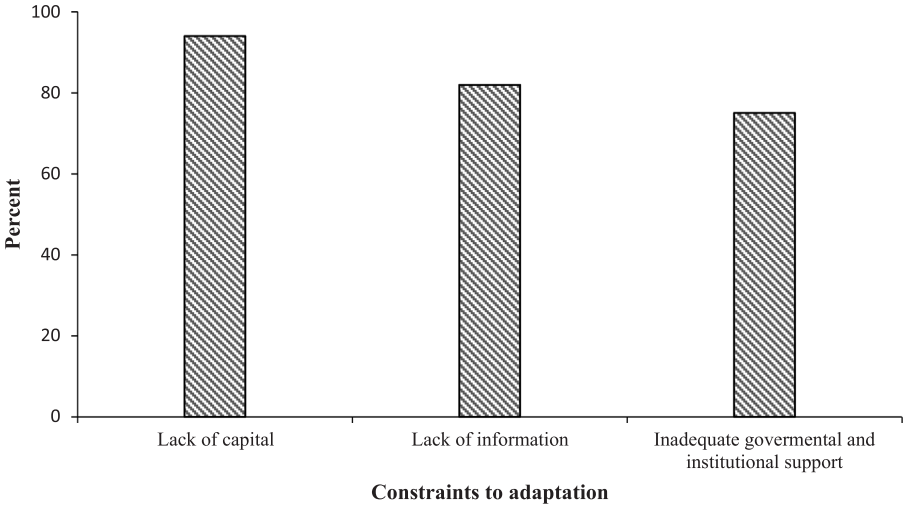

Fig. 3. Constraints to adaptation.

"My solution is we should go for crop diversification. But we should have financial assistance and awareness programmes from the government to go for these adaptation options. …… We can use marginal lands for timber programmes. But some other methods like intercropping programmes can be adopted. For that we need government and institutional support for selecting suitable blocks of land and appropriate crops for the area." [Manager #10, Up-country]

"As crop diversification we have planted rubber. We do not have plan for any other crops other than rubber. Cocoa may be a suitable crop for this area. But we need government and research institutions support to identify exactly whether it is a good crop for the area. We need more awareness programmes." [Manager #23, Mid-country]

Overall, a lack of capital, inadequate access to information and knowledge regarding climate change adaptation, and poor governmental and institutional involvement were commonly cited barriers to climate change adaptation. Hence, appropriate policies to rectify these shortcomings are required in order to help Sri Lanka's tea industry adapt and prosper.

6. Policy implications and conclusions

This research has addressed a gap in the literature around factors affecting uptake of climate adaptation options in perennial agriculture. Uptake of preferred adaptation options in perennial cropping systems can be influenced by many factors. Comprehensive understanding of these factors is key for effective and efficient resource allocation, and for successful adaptation to climate change. We find that estate managers' preferred option for climate adaptation is affected by some factors which are potentially amenable to policy intervention (access to information and company size), and by other factors which are largely outside policy reach (changes in the climate and estate elevation).

Managers of estates which have experienced higher increases in average temperature are more likely to adopt adaptation options such as soil conservation and shade establishment. This makes intuitive sense as both of these practices provide multiple benefits by establishing a cooler micro-climate. Estate managers who have experienced increases in annual rainfall are more likely to prefer shade management as an adaptation option. This may be because shade trees help to shelter tea bushes from the adverse physical effect of increasing rainfall. This suggests that there may be a role for addition research around adaptation strategies such as joint-production of tea and fuel wood trees which could further reduce the impact of increasing temperatures and higher rainfall.

Our results show that managers' adaptation preferences differ significantly with elevation. For example, managers of mid-country and low-country estates are less likely to go for soil conservation than managers of up-country estates. This is probably because the steep up-country topography makes these estates more prone to soil erosion. Managers of mid-country estates are more likely to prefer shade as a climate adaptation option than managers of up-country estates. This is not surprising as up-country tea estates require less shade because temperatures are lower. The terracing and drains required for soil conservation are more expensive investments than tree planting for shade establishment. Up-country estate managers therefore have to be convinced about the long-term benefits of soil conservation before they commit such sizeable investments. This suggests that there is a strong need for further elevation-based research on the impacts of climate change and the effectiveness of different adaptation measures for tea estates at different elevations.

Turning to factors which could potentially be addressed more directly by policy, estate managers with access to information on climate impacts and adaptation options are considerably less likely to prefer crop diversification. Tea estate managers receive information regarding climate change and adaption options through extension services provided by the Tea Research Institute. It is quite possible that these services provide advice which is biased towards retaining current levels of tea production, whether or not this is in the best interests of the estate, the agriculture sector, or the national economy under climate change. This suggests that there may be a role for government in providing tea estates with independent advice formulated around overall national adaptation and development goals.

The study further reveals that estate managers employed by larger companies are more likely to choose diversification as their preferred adaptation option. This is not surprising, as crop diversification requires significant capital investment compared to other adaptation options. This is particularly true for perennial crops such as tea, for which the rate of diversification is very low compared to annual crops; a consequence of the substantial initial investment committed to establish a plantation. Diversification options such as, for example, rubber, cinnamon and timber for fuel wood are less labour intensive in production than tea. Given that large companies are significantly more likely to diversify, this could have a substantial impact on labour demand in rural areas of Sri Lanka – with far-reaching implications for the national economy. This suggests that potential adaptation options for the tea industry – Sri Lanka's largest agricultural employer – should be evaluated holistically to ensure compatibility with sustainable development across all facets of Sri Lanka's agriculture. The survey reveals that tea estate managers feel that they require more information on climate change predictions and their associated impacts to assist their choice of appropriate adaptation options. Policies and practices related

to climate adaptation should be modified in ways that leverage the agriculture sector as a whole, integrating across all related sub-sectors including plantations.

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